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Measurements of $t\bar{t}$ production cross-section with D0 experiment

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The recent measurements of the top anti-top quark pair production cross-section in proton antiproton collisions at $\sqrt{s} = 1.96$ TeV in lepton + jets and dilepton (including tau lepton) channels are presented. These measurements are based on 1 fb^{-1} of data collected with the DO experiment at the Fermilab Tevatron collider. The measured values are compatible with the standard model prediction and have the uncertainty close to the uncertainty of the theoretical prediction $\sim 10\%$.

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I. INTRODUCTION

In the standard model framework the production cross-section of the top quark top antiquark pair ($t\bar{t}$) in proton-antiproton collisions could be calculated in the perturbative QCD approach. The most recent calculations are performed at the next-to-leading order with the next-to-next-leading order soft correction (NLO+NNLO) [1] or at the next-to-leading order with the next-to-leading threshold logarithm correction (NLO+NLL) [2]. The exact value of the calculated cross-section depends on the top quark mass (m_t) and the choice of parton distribution functions (PDFs). For example, choosing CTEQ6.6 parametrization [3] leads to a value of $7.39^{+0.57}_{-0.52}$ pb (for $m_t = 172$ GeV) for [1]. In [2] for CTEQ6.5 PDFs [4] the cross-section value is calculated to be $7.61^{+0.30}_{-0.53}$ (scales) $^{+0.53}_{-0.36}$ (PDFs) pb (for $m_t = 171$ GeV). In both cases uncertainties on the calculated value have two main contributions: uncertainties from the choice of PDF and the renormalization and factorization scales, set to be both equal to m_t. The scales uncertainty is determined by varying both scales from $m_t/2$ to $2m_t$. These scales could be varied simultaneously or independently, and different approaches may affect a lot the scale uncertainty [2]. Despite some what different approaches, both groups [1] and [2] give compatible values for the $t\bar{t}$ cross-section, which are also compatible between different sets of PDFs. The uncertainties on these theoretical predictions are estimated to be less than 8%.

In this overview we report the $t\bar{t}$ production cross-section measurements based on the data collected by the D0 detector between August 2002 and February 2006 with an integrated luminosity of about 1 fb^{-1}. The description of the D0 detector can be found elsewhere [5]. In the standard model the top quark decays to a W boson and a b quark with a probability close to 100%. Here we consider the final state where one W boson decays to a lepton and another one to quarks (lepton + jets final state, branching ratio 38%) and the final state where both W bosons decay to leptons (dilepton final state). For the dilepton final state we consider separately final states with one hadronically decaying tau lepton (3.6%) and final states which contain electron and muon only the latter includes $\tau \rightarrow e, \mu$ decays (6.5%).

II. ELECTRON, MUON DILEPTON FINAL STATES

In order to maximize the acceptance we consider the following final states: the ones with well identified electron or muon (ee, $e\mu$, $\mu\mu$), and the final states with one well identified electron or muon and the reconstructed track (e + track , μ+ track). Selection criteria are optimized in each channel separately to yield the best possible precision. Possible overlaps between different channels are removed by applying veto cuts. The typical identification criteria for an electron require an isolated cluster in the electromagnetic part of the calorimeter with a reconstructed transverse momentum $p_T \geq 15$ GeV. Electron must be matched to a reconstructed track and located in the region $0 \leq |\eta| \leq 1.1$ or $1.5 \leq |\eta| \leq 2.5$, where η is a pseudorapidity defined as $\eta = -ln(\tan(\theta/2))$ and θ is the polar angle with the proton beam. Muon is reconstructed as a track in the muon system, matched to a track from the tracking detector, isolated from the other objects in the calorimeter and in the tracking detector. Muons are required to be within $|\eta| \leq 2.0$ and have $p_T \geq 15$ GeV. Two b quarks from top quark decays reconstructed as jets in the calorimeter using iterative cone

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Channel	Observed	N^{bkg}	BR	L(pb^{-1})	ε
ee	16	3.0	0.01584	1036	8.3 %
$e\mu$ nj=1	16	10.2	0.03155	1046	3.1 %
$e\mu$ nj=2	32	6.7	0.03155	1046	12.4 %
$\mu\mu$	9	3.6	0.01571	1046	5.1 %

TABLE I: Observed event yield, expected background, branching ratio, integrated luminosity and efficiency for dilepton ee, $e\mu$ (1 and 2 jets selections), $\mu\mu$ channels.

Channel	Observed	N^{bkg}	BR	L(pb^{-1})	ε
e+track nj=1	14	1.58	0.1066	1035	0.25 %
e+track nj ≥ 2	8	1.83	0.1066	1035	1.31 %
μ+track nj=1	1	1.38	0.1066	994	0.18 %
μ+track nj ≥ 2	8	1.36	0.1066	994	1.08 %

TABLE II: Observed event yield, expected background, branching ratio, integrated luminosity and efficiency for e+track and μ + track channels with 1 and 2 jets selections.

algorithm [6] with a cone radius of 0.5. Jets should be within $|\eta| \leq 2.5$ and typically are required to have $p_T \geq 20$ GeV, where p_T is corrected for the jet energy scale including the correction for muons from semileptonic b quark decays. In all channels except $e\mu$ a cut on the missing transverse energy corrected for the jet energy scale and muons p_T allows to improve signal-to-background ratio due to the presence of neutrinos from W boson decays. The typical cut value is $20 - 40$ GeV. Additional topological selections exploiting the differences in the signal and background kinematics are applied in each channel. Contribution of the main backgrounds, Z boson events decaying to leptons and diboson events from WW, WZ, ZZ production are estimated from MC simulation using Alpgen or Pythia generators. Data events are used to estimate instrumental backgrounds originating from jets misidentified as electrons or muons from the semileptonic b quark decays and events with large missing transverse energy due to the detector resolution effects. Table I summarizes the observed number of events, expected background and efficiency for the ee, $e\mu$, $\mu\mu$ channels. This allows to measure the $t\bar{t}$ cross-section with 22% precision:

$$\sigma = 6.8^{+1.2}_{-1.1}\ (stat)^{+0.9}_{-0.8}\ (syst) \pm 0.4\ (lumi)\ pb \quad (m_t = 175\ GeV)$$

In the lepton + track channel the signal-to-background ratio is much smaller than in other dilepton channels. In order to improve it an additional requirement that at least one jet is identified as a b quark jet (b-tagging) is applied. The b-jet identification at D0 is based on the neural network, which combines several parameters sensitive to the displaced decay vertices of the B hadrons. A typical cut on the neural network output used by the top analysis allow to tag b quark jets with an efficiency near 54% and the mistagging rate (probability to tag a light quark jet) near 1%. Table II summarizes the observed number of events, expected background and efficiency for the e + track and μ + track final states after applying veto selection on ee, $e\mu$, $\mu\mu$. The jet multiplicity spectra for $t\bar{t}$ signal and backgrounds events are shown on fig. 1. Combination of ee, $e\mu$, $\mu\mu$, e + track and μ + track final states allows to increase the precision of the $t\bar{t}$ cross-section measurement to 19%:

$$\sigma = 6.2 \pm 0.9\ (stat)^{+0.8}_{-0.7}\ (syst) \pm 0.4\ (lumi)\ pb \quad (m_t = 175\ GeV)$$

Systematics uncertainties in dilepton channels come from several sources: jet energy calibration, identification of jets, muons, electrons and tracks, trigger efficiency, instrumental background contribution, background normalization, b-tagging efficiency (for lepton+track only). Many of these sources contribute at the same level and hence there is no "main" systematic uncertainty which can be reduce easily. Instead the laborious work on each source of systematics is required for further improvement.

III. DILEPTON FINAL STATES WITH HADRONICALLY DECAYING TAU LEPTON

Tau lepton is the heaviest lepton and has the strongest coupling to the Higgs boson. Final states with one hadronically decaying tau lepton contains much more background than other dilepton final states, mainly from multijet and W + jets events, but it is interesting to study them because they are sensitive to the contribution from the physics beyond the standard model. For example, if the charged Higgs boson in the minimal supersymmetric standard model scenario has a low enough mass, the $t \to H^+b$ decays will be allowed and will enhance the tau lepton final states.

The tau lepton is identified as a narrow jet in the calorimeter with a cone size 0.3 matched to one or more tracks. The neural network (NN) is used to distinguish tau leptons and jets. The NN input parameters describe energy

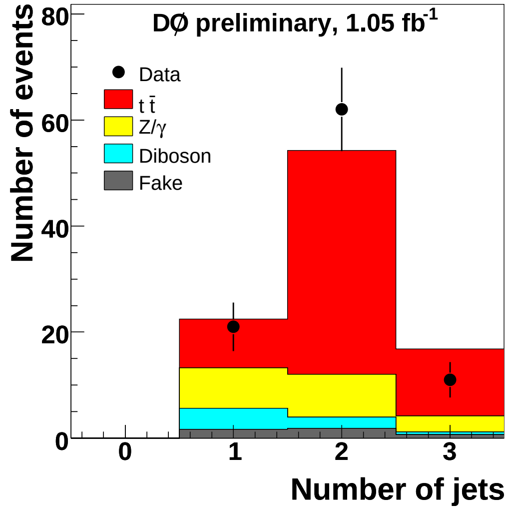

FIG. 1: Jet multiplicity spectra for dilepton and lepton+track channels. The last bin is inclusive.

deposition profile in the calorimeter and track-calorimeter correlations. NN is trained on the MC $Z \to \tau\tau$ sample and on the background sample from real data. The performance of neural network has been verified with $Z \to \tau\tau$ data. For more details see [7]. The event selection for $e\tau$ and $\mu\tau$ final states require at least one tau candidate and one electron with $p_T > 15$ GeV or muon with $p_T > 20$ GeV, at least two jets with $p_T > 20$ GeV and leading jet $p_T > 30$ GeV, transverse missing energy between 15 and 200 GeV. Further improvement of the signal-to-background ratio is reached by the requirement that at least one jet is b-tagged. The main physics background, W+jets and Z+jets, is estimated from MC, and multijet background where jets are misidentified as taus is estimated from data. The measured cross-section has a precision about 30%, where all $t\bar{t}$ dilepton and lepton+jets final states considered as a signal:

$$\sigma = 8.3^{+2.0}_{-1.8}\ (stat)^{+1.4}_{-1.2}\ (syst) \pm 0.5\ (lumi)\ pb \quad (m_t = 175\ GeV)$$

To measure the cross-section times branching ratio we consider only lepton + tau final state as a signal:

$$\sigma(t\bar{t})BR(t\bar{t} \to l\nu_l\tau\nu_\tau b\bar{b}) = 0.19 \pm 0.08\ (stat) \pm 0.07\ (syst) \pm 0.01\ (lumi)\ pb$$

which is compatible with a standard model prediction 0.128 for electron and 0.125 for muon final states.

IV. LEPTON + JETS FINAL STATES

In lepton + jets final state one W boson decays to a lepton (electron or muon) and another one to jets. In this final state two approaches have been used to separate signal from background: kinematic likelihood and b-tagging. In both cases, first we define an inclusive sample selected by requiring exactly one isolated electron or muon with $p_T > 20$ GeV and $|\eta| \leq 1.1$ for electron and $|\eta| \leq 2.0$ for muons, missing transverse momentum ≥ 20 (for e + jets) or ≥ 25 GeV (for μ + jets) and at least three jets with $p_T \geq 20$ GeV and $|\eta| \leq 2.5$. The leading jet must have $p_T \geq 40$ GeV, and the lepton p_T and the missing transverse energy vector must be separated in azimuth to reject background events with mismeasured particles. At this stage the data sample contains only near 20% of $t\bar{t}$ events. The main background originated from W+jets events and multijet events. W + jets events contain real electrons or muons coming from W decays. In multijet events one of the jets is misreconstructed as an electron or produces a muon because of the semileptonic b quark decays. We determine the multijet background contribution in the selected sample by using data samples with the relaxed electron identification or the muon isolation requirements.

In the kinematic likelihood analysis the further improvement of the signal-to-background ratio is reached by using a kinematic determinant built with several variables exploiting the difference in kinematics between $t\bar{t}$ and backgrounds events. For the events with exactly three jets we also use additional requirement that sum of jets transverse momenta is less than 120 GeV. Simultaneous fit of e+jet and μ+jet channels with exactly three jets or with four and more jets allows to extract the number of $t\bar{t}$ and background events. For this we use the discriminant templates from MC for

	3 jets	$\geq$ 4 jets
N_{data}	1760	626
$N_{t\bar{t}}$	245 ± 20	233 ± 19
$N_{W+jets,other}$	1294 ± 48	321 ± 30
$N_{multijet}$	227 ± 28	70 ± 12

	3 jets		$\geq$ 4 jets	
	1tag	$\geq$2tags	1tag	$\geq$2tags
$N_{t\bar{t}}$	147 ± 12	57 ± 6	130 ± 10	66 ± 7
N_{W+jets}	105 ± 5	10 ± 1	16 ± 2	2 ± 1
N_{other}	27 ± 2	5 ± 1	8 ± 1	2 ± 1
$N_{multijet}$	27 ± 6	3 ± 2	6 ± 3	0 ± 2
Total	306 ± 14	74 ± 6	159 ± 11	69 ± 7
hline N_{data}	294	76	179	58

TABLE III: Sample composition for lepton+jets final state in likelihood analysis (left) and b-tagging analysis (right). Number of $t\bar{t}$ events is calculated using the cross-section measured by the likelihood or by the b-tagging analyses correspondingly.

the $t\bar{t}$ signal and $W+$ jets background and from data for the multijet background. The sample compositions for event in the third and forth jet bins is presented in tab. III. The measured cross-section value has a 15% precision:

$$\sigma = 6.6 \pm 0.8\ (stat) \pm 0.4\ (syst) \pm 0.4\ (lumi)\ pb \quad (m_t = 175\ GeV)$$

The b-tag analysis requires that at least one jet is b-tagged. We determine the number of multijet events as above and the number of events expected from other background sources from the number of background events in the inclusive sample multiplied by their probability to be b-tagged. We obtain the b-tagging probability from the MC simulation corrected for differences in the efficiencies observed in the simulation and in data. The composition of the b-tagged samples is given in tab. III . The jet multiplicity spectra for $t\bar{t}$ signal and backgrounds events are shown on fig. 2. The calculated cross-section has a precision of 12%:

$$\sigma = 8.1 \pm 0.5\ (stat) \pm 0.7\ (syst) \pm 0.5\ (lumi)\ pb \quad (m_t = 175\ GeV)$$

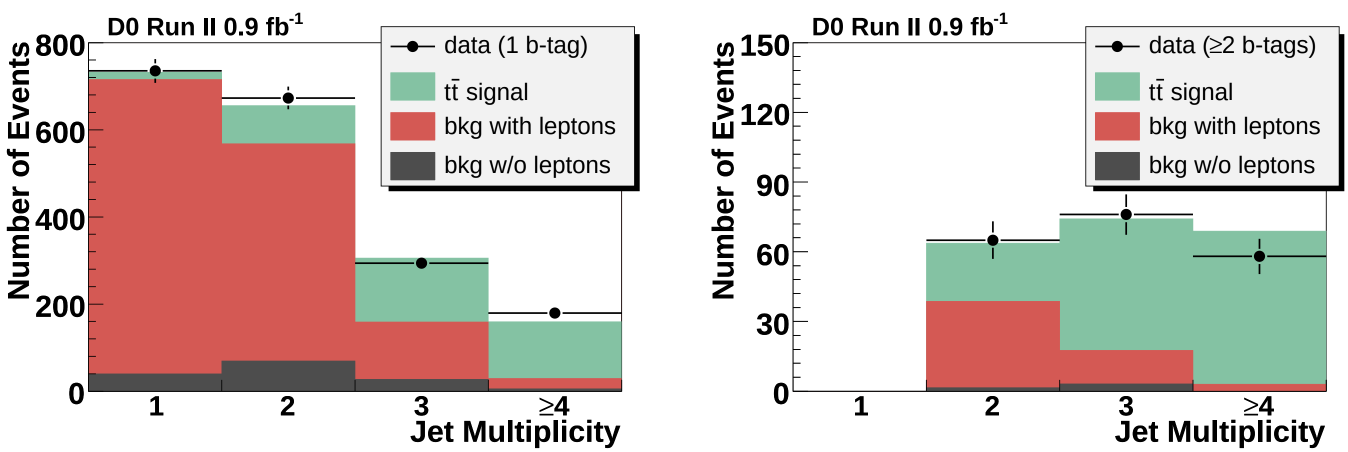

FIG. 2: Jet multiplicity spectra for leptons + jets events with one b-tagged jet (left) and with at least two b-tagged jets (right). The histograms show (from top to bottom) the contributions from $t\bar{t}$ production, from backgrounds with leptons, mainly W + jets, and from the multijet background.

The breakdown of systematics uncertainties is shown in tab. IV. The b-tag analysis systematics is larger than the kinematic likelihood one, mainly because of the systematics on the b-tagging efficiency, but b-tag analysis has better statistical uncertainty due to the better signal to background separation. Combining two results together allows to improve overall precision, because these two results are only partially correlated (statistical correlation factor is 0.31). This combined cross-section value has the relative uncertainty 11%. This is the most precise measurement of the $t\bar{t}$ production cross-section at D0 [8].

$$\sigma = 7.4 \pm 0.5\ (stat) \pm 0.5\ (syst) \pm 0.5\ (lumi)\ pb \quad (m_t = 175\ GeV).$$

V. CONCLUSION

The summary of the D0 $t\bar{t}$ cross-section measurements is shown on fig. 3. All measurements are compatible with the standard model prediction. The uncertainty on the measurement in lepton+jet channel is now close to the theoretical

Source	b-tag	Likelihood	Combined
Selection efficiency	0.26 pb	0.25 pb	0.25 pb
Jet energy calibration	0.30 pb	0.11 pb	0.20 pb
b tagging	0.48 pb	-	0.24 pb
MC model	0.29 pb	0.11 pb	0.19 pb
Multijet bckg normalization	0.06 pb	0.10 pb	0.07 pb
Likelihood fit	-	0.15 pb	0.08 pb

TABLE IV: Breakdown of systematic uncertainties in lepton+jets channel.

uncertainty and will be improved with more statistics collected by D0 experiment. At the end of Run II D0 plans to collect near 8 fb^{-1}. With such integrated luminosity the statistical uncertainty in lepton+jets channel will be near 2% and the total uncertainty will be limited by systematics and, in particular, by the luminosity uncertainty. Assuming the same relative systematics uncertainty as for the current measurement, one can expect to have near 8% precision in the cross-section measurement at the end of Run II. Improving systematics uncertainty by a factor of two will decrease the total uncertainty to approximately 7%. The further improvement is not possible without changing the method of luminosity determination. For example, the possible approach could be to use $p\bar{p} \to Z$ events to normalize cross-section measurement. This approach has an advantage because all correlated systematics uncertainties will be canceled, but it also requires a careful investigation of the correlation between theoretical uncertainties of the Z and $t\bar{t}$ production cross-sections calculation.

Another interesting measurement with the a statistics of Run II is the cross-section ratio of dilepton and lepton+jet channels. In this ratio the luminosity uncertainty and all correlated systematics uncertainties, *e.g.* jet energy scale, jet and lepton ID identifications, will be partially canceled. The precision on this ratio will be limited by the statistical uncertainty in the dilepton channel and could reach 5% or even less.

Cross-section measurement is also useful for the determination of the top quark mass using a theoretical dependence of the $t\bar{t}$ production cross-section on the mass. Such kind of measurements can not compete in precision with the direct measurements, but they are much less dependent on the definition of the top mass parameter in MC generators. The first results of such kind of measurement look quite promising, see *e.g.* [8].

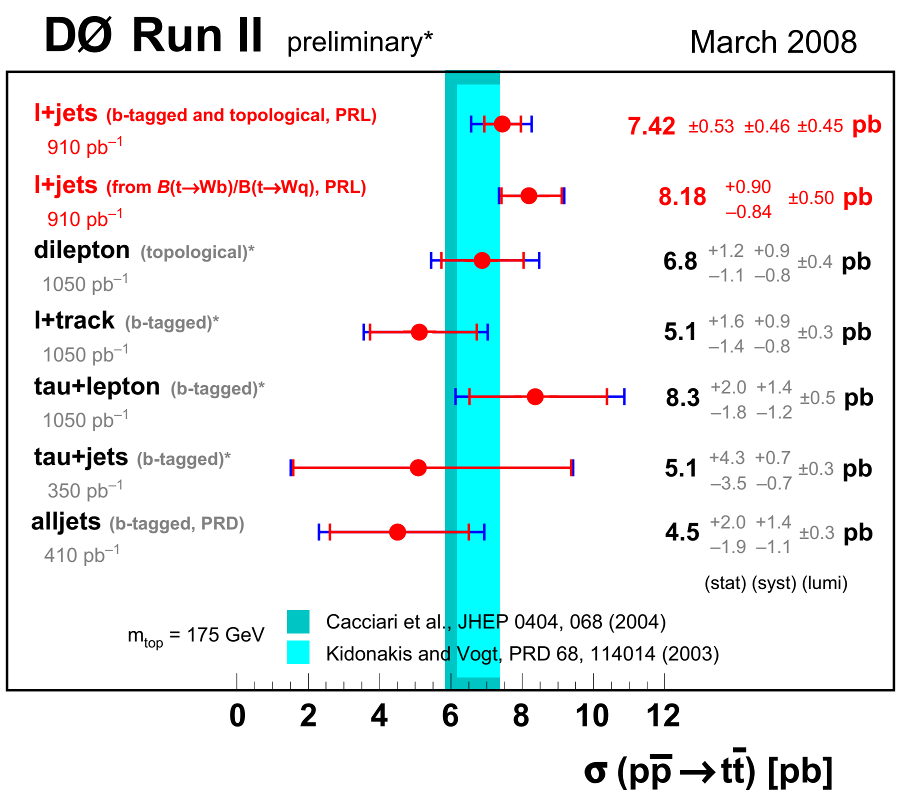

FIG. 3: Summary of the D0 measurements of the $t\bar{t}$ production cross-section.

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